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DE-1 OBSERVATIONS OF POLAR O^+ STREAM BULK PARAMETERS AND COMPARISON WITH A MODEL OF THE CENTRIFUGALLY-ACCELERATED POLAR WIND

C. Wing Ho and J. L. Horwitz
Department of Physics and Center for Space Plasma and Aeronomic Research
The University of Alabama in Huntsville
Huntsville, Alabama 35899

T. E. Moore
Space Sciences Laboratory
Marshall Space Flight Center
Huntsville, AL 35812

Abstract

A survey of bulk parameters of analyzable O^+ outward streams in the mid-altitude (3-4.7 R_E geocentric distance) polar cap magnetosphere is obtained from measurements by the Retarding Ion Mass Spectrometer (RIMS) aboard the Dynamics Explorer-1 (DE-1) spacecraft. There is wide scatter in the obtained densities, but they do display discernible trends: the average O^+ density in these streams decreases from about 60 ions/cc at 3.5 R_E to about 1 ion/cc at 4.6 R_E. The streaming velocities are somewhat more defined, and their average increases from about 8 km/s at 3.5 R_E to about 12 km/s at 4.6 R_E. The densities and bulk velocities are inversely correlated. We have further compared these observational trends with model profiles for the centrifugally-accelerated polar wind as recently described by Horwitz et al. [1994]. The large outflow velocities observed can be understood in part as centrifugally-driven by convection with ionospheric electric field magnitudes of the order 50-70 mV/m, perhaps including plasma expansion effects.

Introduction

Since the discovery of O^+ ions in the magnetosphere [Shelley et al., 1972], there have been numerous efforts to characterize and model outflows of these heavy ions from the polar and auroral ionosphere. Observations of polar O^+ outflows include statistical surveys in the polar topside ionosphere, indicating the upwelling ions flows from the cleft ion fountain [e.g., Lockwood et al., 1985a, Moore et al., 1986; Pollock et al., 1990], the more limited surveys partially characterizing the O^+ flows in the mid-altitude (3-5 R_E) polar cap magnetosphere [e.g., Waite et al., 1985; Lockwood et al., 1985b; Chen et al., 1990; Horwitz et al., 1992], and indications of various dependences of the quantitative outflow fluxes from the polar ionosphere at low-to-medium energies [e.g., Yau et al., 1985]. New measurements of the polar wind from the Akebono spacecraft [e.g., Abe et al., 1993] have begun to reveal features of the profiles of ion outflows in the 2000-10,000 km altitude range, between the topside ionosphere and the mid-altitude polar magnetosphere.

Although O^+ upflow velocities are often found to be or assumed to be quite low ($<$ 1km/s) in and near the topside ionosphere [e.g., Chandler et al., 1991; Abe et al., 1993], the Akebono statistical data of Abe et al. [1993] suggest a broad increase of the bulk outflow velocity from $\sim$ 0 km/s starting at 5500 km altitude to 4-5 km/s at 10,000 km. The limited analyses of Waite et al. [1985], Chen et al. [1990] and Horwitz et al. [1992] in the midaltitude polar magnetosphere showed O^+ streaming velocities of the order 10 km/s, indicating a continuing increase of velocity with altitude. Possible explanations for such profiles of O^+ outward streaming velocities include effects of hot electrons [e.g., Barakat and Schunk, 1983; Ho et al., 1992], enhanced ion heating at low altitudes [e.g., Li et al., 1988], and either of these mechanisms operating over a limited time period or spatial region leading to velocity-filtering effects in the subsequent outflow [e.g., Horwitz and Lockwood, 1985; Gombosi et al., 1985; Wilson et al., 1990]. Most recently, Horwitz et al. [1994] have demonstrated that the natural "centrifugal" parallel acceleration driven by convection [e.g., Cladis, 1986] has significant effects on the polar wind outflow, and produces a strong monotonic increase in the O^+ outflow velocity with altitude for moderate convection regardless of the presence of special heating processes.

It is often difficult to measure the light ion polar wind with spacecraft, chiefly because the generally positive potential on the spacecraft reflects these light ions (which typically have low translational energies relative to the spacecraft) away from the detector. Nevertheless, there are some indirect indications that O^+may often be the dominant species in the outflow. For example, the DE-1 data of Chandler et al. [1991] indicate that near 4000 km altitude, the density ratio of O^+ to H^+ might be of the order 20. Using such values of H^+ and O^+ densities and also velocities [Chandler et al., 1991] as lower boundary conditions in the calculation of ion bulk parameter profiles with a steady-state semikinetic model of the H^+ and O^+ polar wind, together with warm ion and electron temperatures (e.g., 5000 and 9000 K, respectively) Ho and Horwitz [1993] showed that the O^+ density would remain the dominant ion to very high altitudes (8 R_E), and that the resulting total density profile (dominantly O^+) matched extremely well the average electron density profile obtained from DE-1 plasma wave measurements by Persoon et al. [1983].

The purpose of this paper is to present analyzed bulk parameters (density, and outward streaming flow velocity) for core O^+ for the 3-5 R_E range for several DE-1 passes in which the fluxes were sufficient for analysis in terms of bulk parameters. We will further show that the trends as seen in these and previous O^+ outflow streaming velocities are consistent with effects of centrifugally-driven acceleration by convection with ionospheric electric field magnitudes of the order 50-70 mV/m, perhaps together with plasma expansion effects.

Survey of Core O^+ Bulk Parameters from DE-1

The DE-1 spacecraft was launched in August, 1981 into an elliptical polar orbit with apogee of about 4.6 R_E. The Retarding Ion Mass Spectrometer (RIMS) [Chappell et al., 1981] on DE-1 included a radial head which measured ion distributions streaming along the magnetic field line. This radial head performed retarding potential analysis sweeps from 0 to 50 eV during the period of about October 19 – November 28, 1981. Here we will present results of bulk parameter analysis of O^+ streams for eleven DE-1 passes through the mid-altitude northern hemisphere polar cap magnetosphere. We examined several other periods for which the O^+ fluxes were too low (less than 4×10^5 $cm^{-2}s^{-1}$) to be analyzed. Hence, the data presented here will not be indicative of O^+ characteristics for the polar cap at all times, but rather for those streams with more enhanced O^+ fluxes.

Apart from the method for dealing with spacecraft potential effects, the analysis programs utilized here are essentially the same as used by Waite et al. [1985] and Chen et al. [1990]. For each time period analyzed, we first analyzed the angular distributions of 0-50 eV O^+ fluxes to determine the spin angle of maximum flux (streaming direction). We then obtained the retarding potential (RPA) curves (fluxes vs. retarding potential) obtained over a narrow angular range about the streaming direction. These curves were fit to RPA curves with RIMS response for flowing Maxwellian ion distributions; thus obtaining the best fit to the data of Maxwellian parameters of density, temperature and streaming velocity. However, we do not display the temperatures obtained from this analysis because the the corresponding thermal energies were generally found to be smaller than the energy spacing between the determining RPA steps for the large flow energies seen and thus below the minimum resolvable temperatures. The streaming velocities shown are appropriate to the spacecraft reference frame, which was moving at 1-3 km/s in the frame of the Earth for these cases.

One of the uncertainties in such bulk parameter analysis is the value of the satellite potential (Φ_{sp}), the choice of which will affect the values of the calculated bulk parameters. One approach, used by Waite et al. [1985] for example, is to obtain RPA fits for the bulk parameters for a set of predetermined Φ_{sp}, and to present the derived bulk parameters for the different possible Φ_{sp}. Here, we use a somewhat different iterative method. For each sample for analysis, we obtained an initial estimate of the expected or average total density from the spacecraft geocentric distance and the electron density profile of Persoon et al. [1983]. This led to an initial estimate of Φ_{sp} from the density-Φ_{sp} empirical relations derived from data from several spacecraft by Comfort et al. [1988]. This was then used as a constraint parameter in our first RPA bulk parameter analysis of the particular sample, which resulted in a new density estimate for O^+. This data-based O^+ density estimate was then combined with an estimate of the H^+ polar wind density at that altitude from a model essentially as in the Ho and Horwitz [1993] work to obtain a new estimate for the total density. (For lack of better information on H^+ in general at these altitudes, the low-energy H^+ needed to be approximated by a model in this way. The H^+ densities approximated in this way turned out to be sufficiently small that they had little effect on the O^+ density estimates.) This new total density estimate led to a new estimate of Φ_{sp}, and the RPA fit was repeated. The procedure was iterated until Φ_{sp} and the density converged.

Figure 1 shows the core O^+ density and streaming velocity data plotted versus geocentric distance, obtained from portions of DE-1 passes above 70° invariant latitude in the northern hemisphere during November 1981. Each data point in Figure 1 represents an average over one, two or five minutes of observation, depending on the count rate. The dotted line in each panel is the weighted average of the data samples calculated in bins of size of 0.25 R_E, while the solid line is the anti-logarithm of the average of the logarithm of the data.

The O^+ densities plotted display considerable variation, with scatter of up to two orders of magnitude for a given altitude range. Nevertheless, the trends in the averages do indicate that, for this class of O^+ streams, the O^+ densities decline from about 60 ions/cc at 3.5 R_E to about 1 ion/cc at 4.6 R_E. The scatter in the bulk streaming velocities is more confined, and the averaged profiles suggest a slight general increase from about 8 km/s at 3.5 R_E to about 12 km/s near 4.6 R_E. Figure 2 shows the correlation of O^+ densities and velocities. The data are moderately scattered in the density range of 1 – 10 /cc. However, the binned averages show that high O^+ densities are in general inversely related to the velocities. The O^+ flux is found to vary from 10^9 cm^{-2}s^{-1} at $\sim$ 3 R_E to 10^8 cm^{-2}s^{-1} at $\sim$ 4.6 R_E (not shown).

Comparison of Observed and Modeled O^+ Profiles

We now compare, in Figure 3, the averaged core O^+ bulk parameter profiles (shown as black dots with error bars) from Figure 1 with profiles from a semikinetic model for polar plasma outflow. For these model profiles, we specify H^+ and O^+ densities and flow velocities at our 1.6 R_E lower boundary as H^+(O^+) densities of 5 (300) cm^{-3} and flow velocities of 10 (0) km/s, respectively. These are the same as the winter averages of Chandler et al. [1991] at this altitude. The lower boundary temperatures used were 5000 K for ions and 9000 K for electrons, this is the same as the lower boundary temperatures used by Ho and Horwitz [1993]. The chosen lower boundary temperatures are also comparable to the recent Akebono observations by Abe et al. [1993], who have reported O^+ temperatures at 5000 km altitude in the range 10^4 - 2×10^4 K in the dayside polar cap, and 3×10^3 K - 7×10^3 K in the nightside; and the majority of data presented in this paper are measured during DE-1 passes on the nightside.

The semikinetic model includes the effect of centrifugal parallel ion acceleration by convection electric fields as discussed by Horwitz et al. [1994]: The dash, dot-dash, solid and triple dot-dash profiles correspond to ionospheric convection electric fields of 0, 50, 70 and 100 mV/m, respectively. In addition, we have included the velocity profile for the free expansion of the polar wind into a vacuum at 2000 seconds after the initial polar wind expansion with an ionospheric electric field of 50 mV/m (dotted curve). Note that the lower boundary density (180 cm^{-3}) assumed for the case of zero convection electric field is somewhat different from the other cases. The null electric field case has boundary conditions that are exactly the same as examined by Ho and Horwitz [1993], which produces a density profile closely matches the average DE-1 electron density profile obtained by Persoon et al. [1983]; while the other cases assume a density at the lower boundary of 300 cm^{-3} resulting in density profiles which match better the observed O^+ densities. Both values of O^+ density at lower boundary used in the model are within the error margin of Chandler et al. [1991] for the winter season. Finally, we have also shown (as plusses) the Akebono O^+ velocity profile from Figure 3 of Abe et al. [1993] in the lower altitude range of the velocity panel here.

If we first focus on the velocity panel of Figure 3, we note that the DE-1 average O^+ data for these streams bears a reasonably close resemblance to the modeled velocity profile for both the E_i= 70 mV/m steady-state case (solid) and the E_i= 50 mV/m, t=2000 sec plasma expansion case (dotted). The Akebono (plusses) average profile wavers considerably in altitude, but is perhaps broadly centered about the same model velocity profiles. Certainly it can be seen that the steady-state polar wind model without centrifugal acceleration has much lower velocities than indicated by the observations (see also Horwitz et al. [1994] for theoretical comparison). The model density profiles also approximately bracket the range of the observational densities from about 3.5 to 4.6 R_E. These density profiles are somewhat higher than the electron density profile of Persoon et al. [1983] (essentially the dashed model curve) but the shape dependence with geocentric distance is similar.

Discussion

In this paper, we have presented a first though quite limited survey and empirical profile of O^+ bulk parameters for analyzable upgoing streams in the midaltitude (3-5 R_E) polar cap magnetosphere, and we have performed some comparison of these empirical profiles with those of the centrifugal polar wind [Horwitz et al., 1994]. It is readily apparent that the observed streaming velocities show the most definitive values and trends, increasing from near 8 km/s at about 3.5 R_E to about 12 km/s, and that this empirical velocity profile fits those of characteristic enhanced polar wind profiles at either steady-state conditions of ionospheric convection electric fields of the order E_i=70 mV/m or at about 2000 seconds after plasma expansion in an E_i=50 mV/m convection field. We therefore tentatively conclude that these streams are likely to be accelerated significantly by such centrifugal effects, and probably by velocity-filtering effects associated with temporal plasma expansion. Both features certainly occur if many of these streams originate in the cleft ion fountain and are convected through the polar cap [e.g.,Lockwood et al., 1985; Horwitz and Lockwood, 1985].

Regarding the density profiles, we noted that the observed densities show a decline with altitude whose shape is not inconsistent with that obtained by Persoon et al. [1983] but is overall a factor of 2-4 larger in the geocentric distance range 3.8-4.6 R_E. This may not be surprising insofar as the analyzable streams considered here would not include lower density populations likely to have been included in the Persoon et al. [1983] average, although there were also a number of circumstances in the Persoon et al. [1993] that appear to have limited polar cap electron density analysis from their plasma wave measurements.

The present analysis technique does not permit a reliable estimate of the O^+ temperature, because the RIMS energy steps are exponentially spaced, the minimum resolvable temperature at the 10 km/s bulk velocity range is about 10^4 K. A plausible way to estimate the temperature is to use the width of the spin curves (ratio of thermal to bulk flow speed). Ideally, we would like to obtain an empirical model from a far more extensive data base that would allow construction of a three-dimensional empirical description including local time and latitudinal variations, and of course further dependences on magnetic activity and season, etc. Such data may come from the Thermal Ion Dynamics Experiment (TIDE) to be flown on the upcoming NASA POLAR mission. It may also be possible to obtain further statistical information on some of the core O^+bulk parameters from the DE-1 data set even after the radial RPA head failure which limited the present survey(e.g., M. O. Chandler, private communication, 1994).

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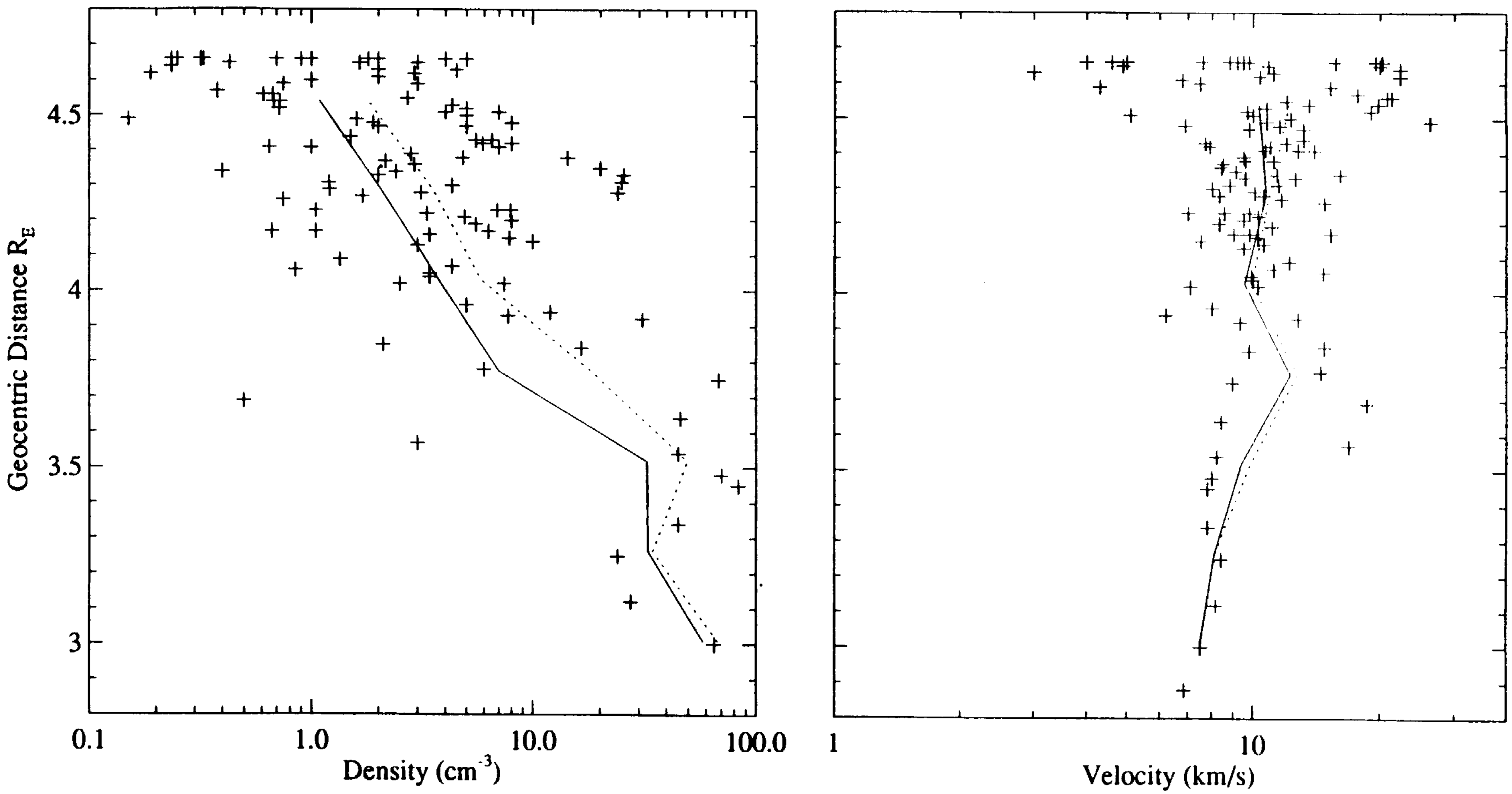
Figure Captions

Figure 1. Polar cap O^+ bulk parameters obtained from DE1/RIMS. The dotted lines represent the averages of the particular data parameters within bins 0.25 R_E wide in altitude. The solid lines correspond to the anti-logarithm of the average of the logarithms of the data within the same altitudinal bins.

Figure 2. Correlation of O^+ densities and streaming velocities. The data are binned into 10 bins of equal size in the logarithm of the O^+ densities. the binned data (black dots) have been smoothed with a boxcar average of every two binned data points.

Figure 3. Observed O^+ bulk parameters (represented by black dots, same as in solid lines in Figure 1) and modelled O^+ profiles. The plusses in the velocity panel are from the Akebono polar low-altitude profile of Abe et al. [1993]. The dash, dot-dash, solid and triple dot-dash profiles correspond to ionospheric convection electric fields of 0, 50, 70 and 100 mV/m, respectively, for the centrifugal polar wind model [Horwitz et al.,1994]. In addition, we have included the velocity profile for the free expansion of the polar wind into a vacuum at 2000 seconds after the initial polar wind expansion with an ionospheric electric field of 50 mV/m (dotted curve).



Geocentric Distance R_E
4.5
4
3.5
3
0.1
1.0
10.0
100.0
Density (cm^{-3})
1
10
Velocity (km/s)

Figure 1

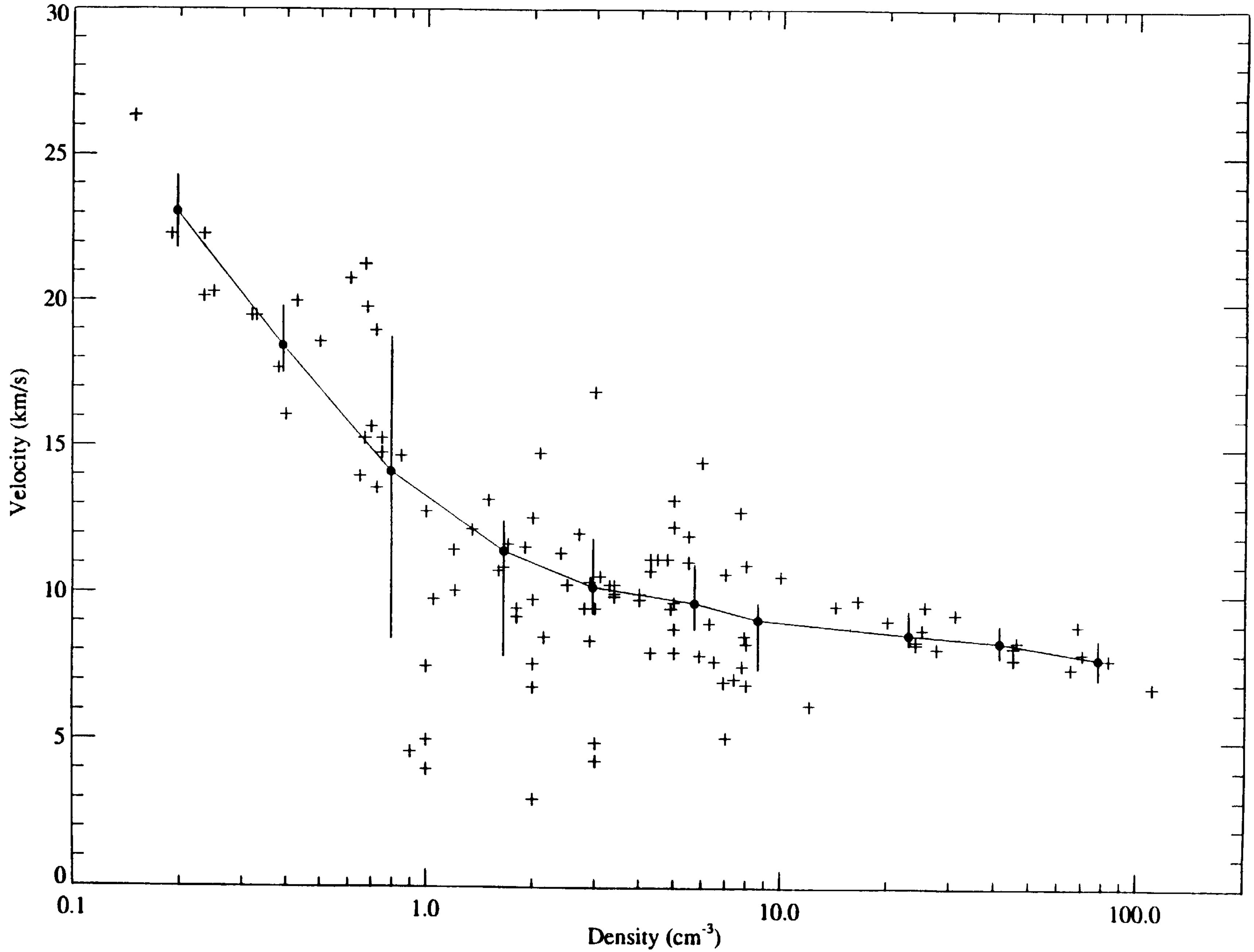


Fig 2

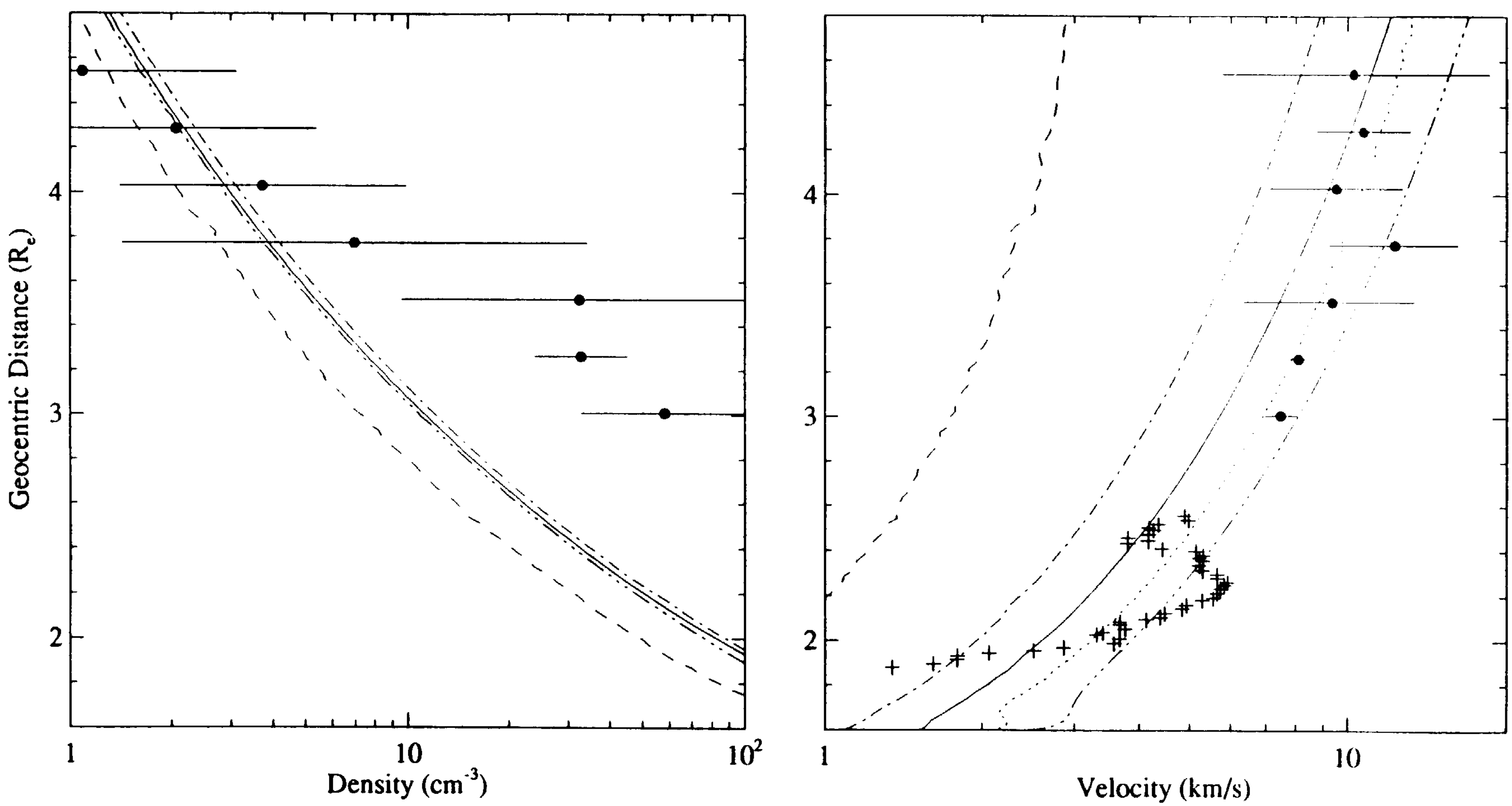


Figure 3